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Study 84-343

This manuscript has been submitted to the
Journal of Hydraulic Research
for publication and the contents are
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LABORATORY VERIFICATION OF A MOBILE BOUNDARY, UNSTEADY FLOW MODEL (MOBED)

by

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April 1984

MANAGEMENT PERSPECTIVE

This mathematical model of channel and bottom sediment flows is the most versatile and accurate contribution available today. Not only is no calibration required, but the model deals with ever changing flow rates and sediment supply rates which prevail in real life.

As well as the tests described here the model has been used for various real situations successfully. It should be adopted as one of the standard tools in the analysis of channel and river flow.

T. Milne Dick
Chief
Hydraulics Division

PERSPECTIVE DE GESTION

Ce modèle mathématique des écoulements de sédiments dans le chenal et au fond est le plus souple et le plus précis actuellement disponible. Non seulement ne nécessite-t-il aucun étalonnage, mais il permet également de tenir compte des variations ininterrompues du débit et du taux d'approvisionnement en sédiments qui existent en réalité.

En plus de permettre les essais décrits ici, le modèle a été utilisé avec succès dans diverses situations réelles. Il devrait être adopté à titre d'instrument type d'analyse de l'écoulement dans les chenaux et cours d'eau.

T. Milne Dick
Chef de la Division de l'hydraulique

SUMMARY

A set of laboratory experiments to verify a mobile boundary, unsteady flow model developed at the Hydraulics Division, National Water Research Institute in Burlington, Ontario, Canada is described. The model solves the St. Venant equations and a sediment mass balance equation using finite difference approximation and uses a general expression to evaluate the energy slope, enabling the model to be used with different friction factor relations. The sediment transport rate required for sediment mass balance is computed using the Ackers and White relationships. The model predictions carried out with the use of friction factor relations of Kishi and Kuroki agree very well with the measured profiles of water and bed levels, indicating that the model is capable of yielding realistic predictions of mobile boundary flow characteristics.

RÉSUMÉ

On décrit un ensemble d'expériences en laboratoire destinées à vérifier un modèle d'écoulement varié non permanent sur fond mobile mis au point par la Division de l'hydraulique de l'Institut national de recherche sur les eaux de Burlington (Ontario), Canada. Le modèle permet de résoudre les équations de St-Venant ainsi qu'une équation d'équilibre massique des sédiments par approximation des différences finies et fait appel à une expression générale d'évaluation de la pente énergétique, ce qui en rend possible l'utilisation pour différentes relations du facteur de frottement. La vitesse de transport des sédiments, nécessaire dans l'équation d'équilibre massique, est calculée au moyen des relations d'Ackers et White. Les prévisions obtenues pour les relations du facteur de frottement de Kishi et Kuroki correspondent très bien aux profils mesurés des niveaux d'eau et du lit, ce qui indique que le modèle permet de prévoir les caractéristiques d'écoulement sur fond mobile de façon réaliste.

1 INTRODUCTION

A mobile boundary flow model called MOBED capable of predicting unsteady flow characteristics in natural streams has been developed at the Hydraulics Division of the National Water Research Institute of Burlington, Ontario, Canada. The model solves the St. Venant's equations and a sediment mass balance equation numerically using the finite difference approximation. The energy slope appearing in the momentum equation is evaluated using a general expression which enables the use of different friction factor relations into the model without affecting its algorithm [1]. Complete details of the model are given in a user manual [2] and its update [3]. In this paper, a set of experiments carried out in a laboratory flume to verify the model is described together with the comparison of model prediction and measurement.

2 EXPERIMENTAL SETUP

Experiments to verify MOBED were carried out in the sediment transport flume of the National Water Research Institute. The flume is a tiltable one measuring 2 m in width and 22.8 m in length. Water from a constant head tank enters the flume through an inlet pipe, a diffuser and a head box. The flow rate is controlled by a butterfly valve fitted to the inlet pipe and is measured using an "anubar" flow meter. A uniform flow distribution across the flume is ensured by the installation of baffles and flow straightners in the head box.

At the downstream end, a louvre type tailgate is installed to control the flow depth. Water from the flume discharged into three large metal containers which served as sediment traps before emptying into the sump. A provision to measure the flow rate and sediment transport rate through the central one-third of the flume width is available which eliminates the need for accounting for wall effects. The sediment is fed into the flume from a hopper through a rotating shaft with longitudinal grooves around its periphery. The rate of sediment feed is adjusted by controlling the speed of rotation of the shaft. The flume is also equipped with a carriage to support the instruments. The carriage is driven by an electric motor and traverses along the length of the flume at three different speeds of 5, 10 and 15 cm/s. A general view of the flume is shown in Fig. 1.

The instruments mounted on the carriage include a water level indicator and a bed level indicator. The water level indicator is a conductivity type instrument consisting of a point gauge that follows the water level by maintaining contact with the water surface at all times. The bed level indicator is an optical instrument which follows the bed contour by maintaining a constant gap between the flume bed and the tip of the instrument. The signals from these instruments were recorded on a XYY' strip chart recorder along with a signal to measure the distance traversed by the carriage along the length of the flume. The view of the instruments mounted on the carriage is shown in Fig. 2.

3 EXPERIMENTAL PROCEDURE

The laboratory verification of MOBED was carried out using two different sets of experiments. In the first set of experiments, details of which are given elsewhere [4], the water supply rate was held steady and the degradation and the aggradation of stream bed that occur as in result of under or over supply of sediment were measured and compared with the model predictions. In the second set of experiments which are described here, the sediment

supply rate was held constant and the water supply rate was varied in steps as shown in Figs. 3 and 4.

Figure 3 is for Run No. 1 and Fig. 4 is for Run No. 2. In Run No. 1, the water supply rate was decreased initially and then increased back to its original value, whereas in Run No. 2, the variation was exactly the opposite. In both of these runs, the sediment supply rate was constant at 0.06 kg/sec. The flume bed was covered with a fairly uniform sand of medium size 1.2 mm. The profiles of water level and bed level were recorded every ten minutes from the start of the run by traversing the carriage through the working length of the flume which is 14.40 m long. The profiles measured at instants shown in Figs. 3 and 4 are depicted in solidlines in Figs. 5 to 16 for both runs.

4 MODEL SIMULATIONS

The flows tested in both runs were simulated using MOBED. The input data required for the model consist of following items:

1) initial conditions
2) boundary conditions for flow
3) boundary conditions for sediment flux
4) sediment characteristics
5) shape of flow cross-sections

A brief description of each of the above items is given below together with the actual values and/or the information used in the present simulations.

1) Initial profiles: The flow rate, the flow depth and the bed level profile as a function of distance along the reach being modelled at the beginning of the simulation period constitute the initial conditions for the model. In the present simulations, the initial conditions were extracted from the bed and water level profiles measured at the beginning of each run, i.e. from the Figs. 5 and 11.

2) Boundary conditions for flow: In MOBED, there are altogether six options for the specification of flow boundary conditions. They are summarized in Table 1.

TABLE 1. Different options for the specification of boundary conditions in MOBED

Boundary / Options	Upstream Boundary	Downstream Boundary
1	flow rate vs time	flow depth vs time
2	flow depth vs time	flow rate vs time
3	flow rate vs time	stage-discharge relation
4	flow depth vs time	stage-discharge relation
5	stage-discharge relation	flow rate vs time
6	stage-discharge relation	flow depth vs time

For the present simulations, option 1 was adopted. The flow rate as a function of time at the upstream boundary was provided

by Figs. 3 and 4 and the flow depth vs time at the downstream boundary was determined from the water level profile measurements.

3) Boundary conditions for sediment flux: Information regarding the variation with respect to time of sediment supply rate at upstream and downstream boundaries is required as input data to model MOBED. In the present simulations a constant sediment supply rate of 0.06 kg/sec was specified at the upstream boundary and at the downstream boundary. It was equated to the transporting capacity of flow.

4) Sediment characteristics: In the current version of MOBED, the sediment transport rate is calculated using the relations of Ackers and White [5] and the energy slope is calculated using the friction factor relations of Kishi and Kuroki [6] which account for the energy loss due to bed-form roughness of alluvial stream beds. The details of these two methods can be found in Ref. [2]. As input to these methods, the following sediment characteristics are required:

   1) sediment sizes, D_{35} and D_{65} (D_i denotes the size for which i% of material by weight is finer)

   2) specific gravity of sediment

   In addition, the porosity of the sediment bed is required to compute the change in bed levels knowing the net change in sediment flux within a control volume. A measured value of 0.4 was used for the present simulations.

5) Shape of flow-cross sections: Information regarding the shape of flow cross sections at a number of sections within the reach of a river being modelled is necessary to compute the geometric characteristics such as the flow cross-sectional area, the wetted perimeter, the top width and a parameter signifying the non-prismatic nature of the channel. In MOBED, the shape of a cross-section is given in terms of lateral distance and elevation of a number of points along the perimeter of the river boundary. From this data the model computes the geometric characteristics at different flow stages which are then used in the interpolation of geometric characteristics for a particular flow stage. When the sections for which the geometric data are specified do not coincide with the computational grid sections, values corresponding to the closest section are used. In the present simulations, a rectangular cross-section of 2 m wide and 1 m deep was specified to the model at the first computation grid section.

5 RESULTS AND DISCUSSION

The simulated water and bed levels for both runs are shown in Figs. 6 to 10 and 12 to 16 as discrete points. Fig. 5 shows the initial conditions of water and bed profiles for Run No. 1 as dotted lines drawn through the measured profiles and Fig. 11 shows the same for Run No. 2. In specifying the initial condition for bed levels for both the runs, average lines are drawn through the measured profiles using eye judgement. It should be pointed out that in the

present simulation of bed profiles, the objective was not to predict the movement of microscale bed features such as dunes and ripples but to consider the large scale undulation which affect the slope of the reach being modelled. That is why the predicted bed levels do not follow the shape of individual dunes that were present, but give the variation of an average bed level. The movement and dispersion of the aggradation front evident in initial bed level (see Fig. 3 and Fig. 11) can be noticed in the trend of the predicted bed levels in Figs. 6 to 10 and 12 to 16.

The predicted water levels agree very well with the measured profiles giving credibility to model predictions. Even though the movement of the bed forms was not considered in the model, the effects of bed forms on frictional characteristics of mobile boundary flows are adequately described by the equations of Kishi and Kuorki [6] as evidenced by the close agreement between model predictions and measured water level profiles. As for the adequacy of the sediment transport rate relationships employed in the model, a better test was provided by the set of experiments reported in Ref. [4] dealing with the degradation and aggradation of channel bed resulting from under or over supply of sediment respectively. These two studies clearly demonstrate that MOBED is capable of yielding realistic predictions of unsteady flows in mobile boundary channels.

It is interesting to point out that the prediction of MOBED were carried out without having to calibrate the model. In fact, all the model parameters are measurable quantitites and as such do not require calibration procedure to establish their values. In contrast, some of the existing models such as the one developed by Y.H. Chen [7] which employ Manning's equation to compute energy slope require calibration to establish the value of Manning's 'n'. Besides, the use of Manning's equation for mobile boundary flows is not convenient because the value of 'n' changes as the flow intensity changes owing to the changes in the bed form geometries. Therefore, a model with Manning's 'n' calibrated for a certain range of flow intensities may not yield realistic predictions for a different range of flow intensities.

As indicated earlier in the introduction, in MOBED a general expression was employed to compute the energy slope that appear in the momentum equation. The form of this expression is such that most of the existing friction factor relations of both rigid boundary and mobile boundary flows can be brought to this form. As a result, the model can be run with different friction factor relations without affecting the program structure. Therefore, MOBED can be considered as the most versatile of the existing river flow models.

6 CONCLUSION

The laboratory experiments described here indicate that MOBED is capable of yielding realistic predictions of water and bed level variations under unsteady flow conditions and that the friction factor relations of Kishi and Kuroki used in the model are adequate to describe the frictional characteristics of mobile boundary flows. MOBED employs a general expression for energy slope which renders the model the most versatile of the existing river flow models.

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FIGURES

Fig. 1 General view of sediment transport flume

Fig. 2 View of instruments mounted in the flume

Fig. 3 Variation of water supply rate at flume entrance as function of time (Run No. 1)

Fig. 4 Variation of water supply rate at flume entrance as function of time (Run No. 2)

Fig. 5 Initial bed and water levels used as input to model (Run No. 1)

Fig. 6 Comparison of model predictions with laboratory measurements at instant A (Run No. 1)

Fig. 7 Comparison of model predictions with laboratory measurements at instant B (Run No. 1)

Fig. 8 Comparison of model predictions with laboratory measurements at instant C (Run No. 1)

Fig. 9 Comparison of model predictions with laboratory measurements at instant D (Run No. 1)

Fig. 10 Comparison of model predictions with laboratory measurements at instant E (Run No. 1)

Fig. 11 Initial bed and water levels used as input to model (Run No. 2)

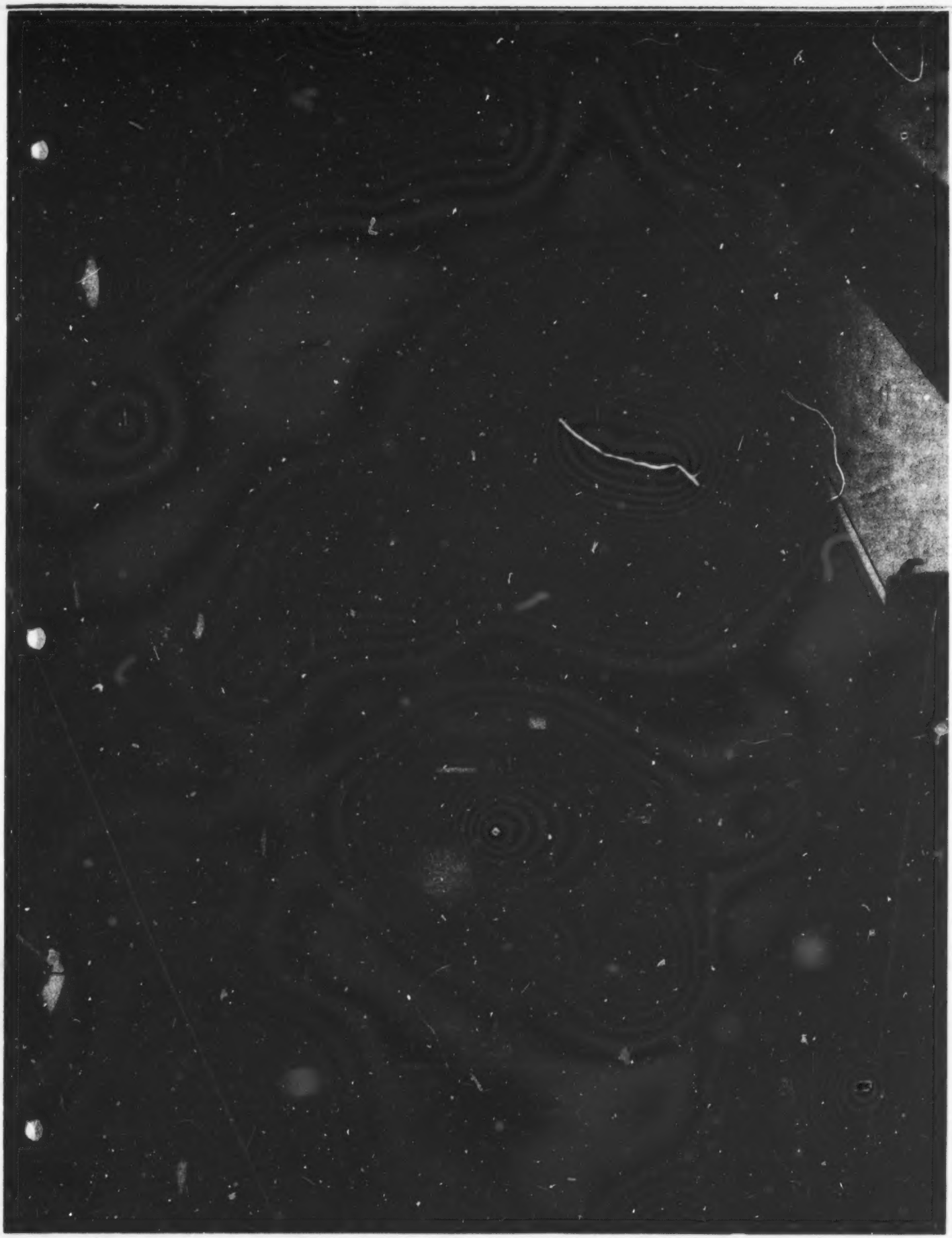
Fig. 12 Comparison of model predictions with laboratory measurements at instant A (Run No. 2)

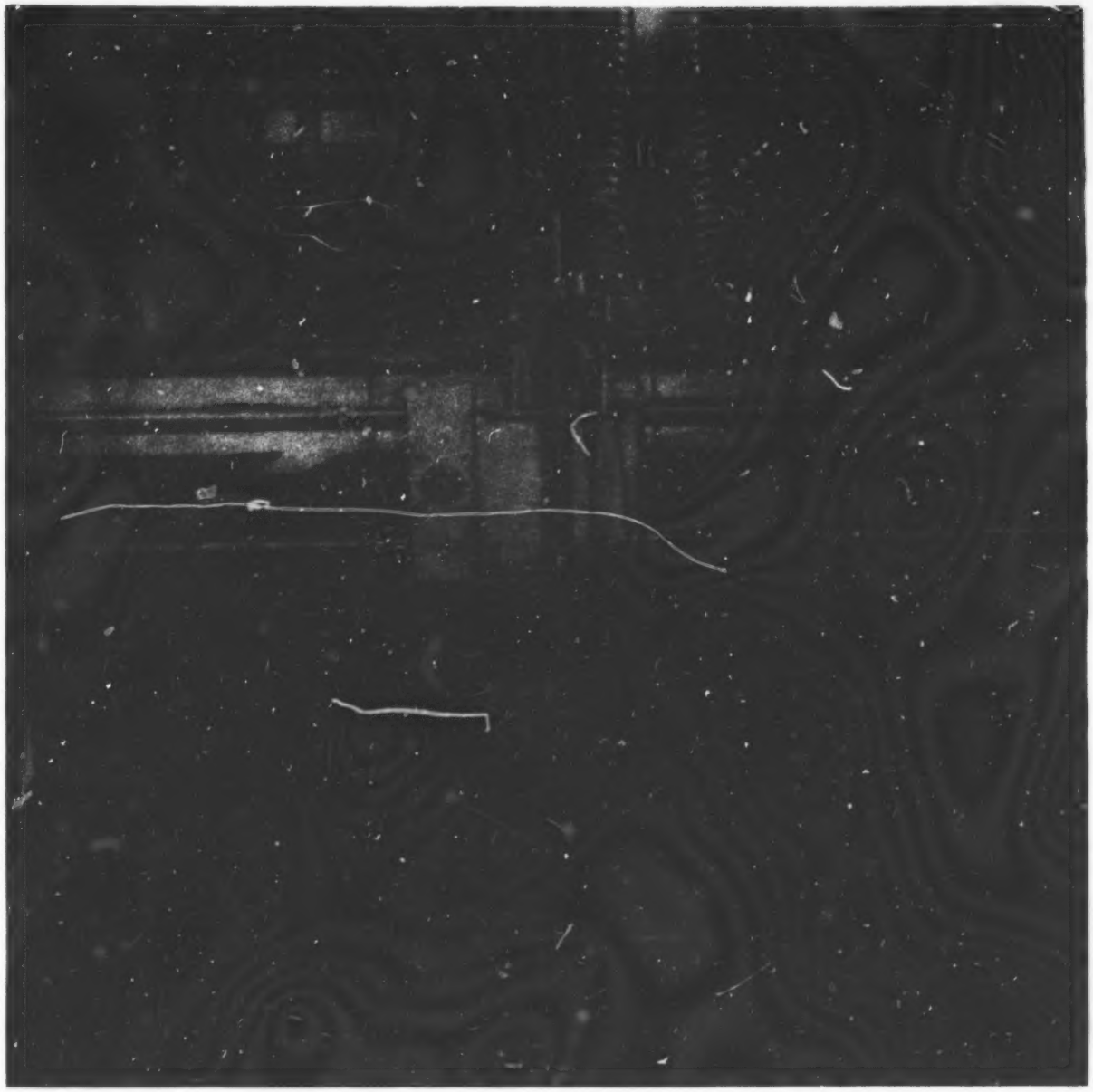
Fig. 13 Comparison of model predictions with laboratory measurements at instant B (Run No. 2)

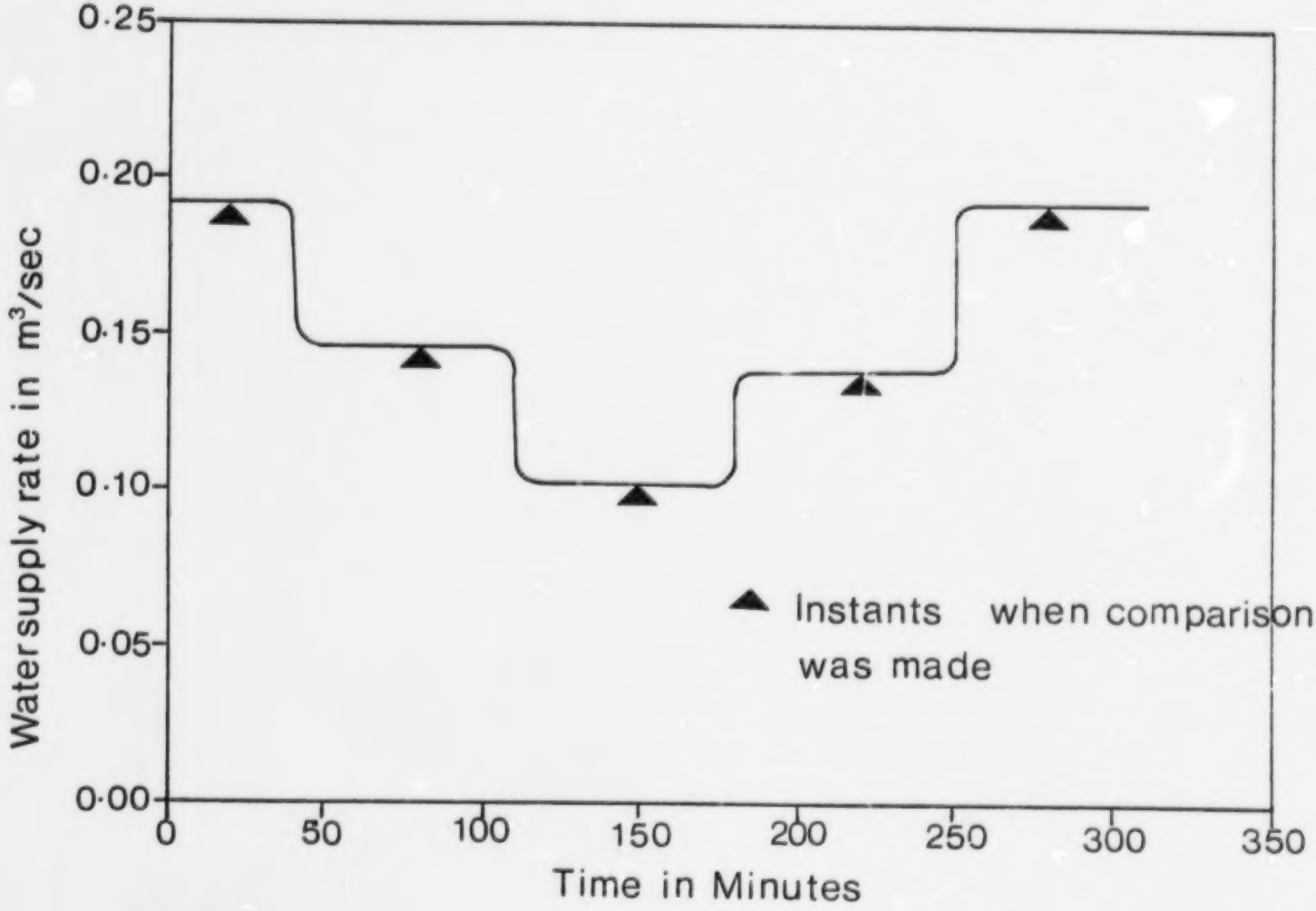
Fig. 14 Comparison of model predictions with laboratory measurements at instant C (Run No. 2)

Fig. 15 Comparison of model predictions with laboratory measurements at instant D (Run No. 2)

Fig. 16 Comparison of model predictions with laboratory measurements at instant E (Run No. 2)



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Water supply rate in m³/sec
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350
Time in Minutes
Instants when comparison was made

FIGURE 3

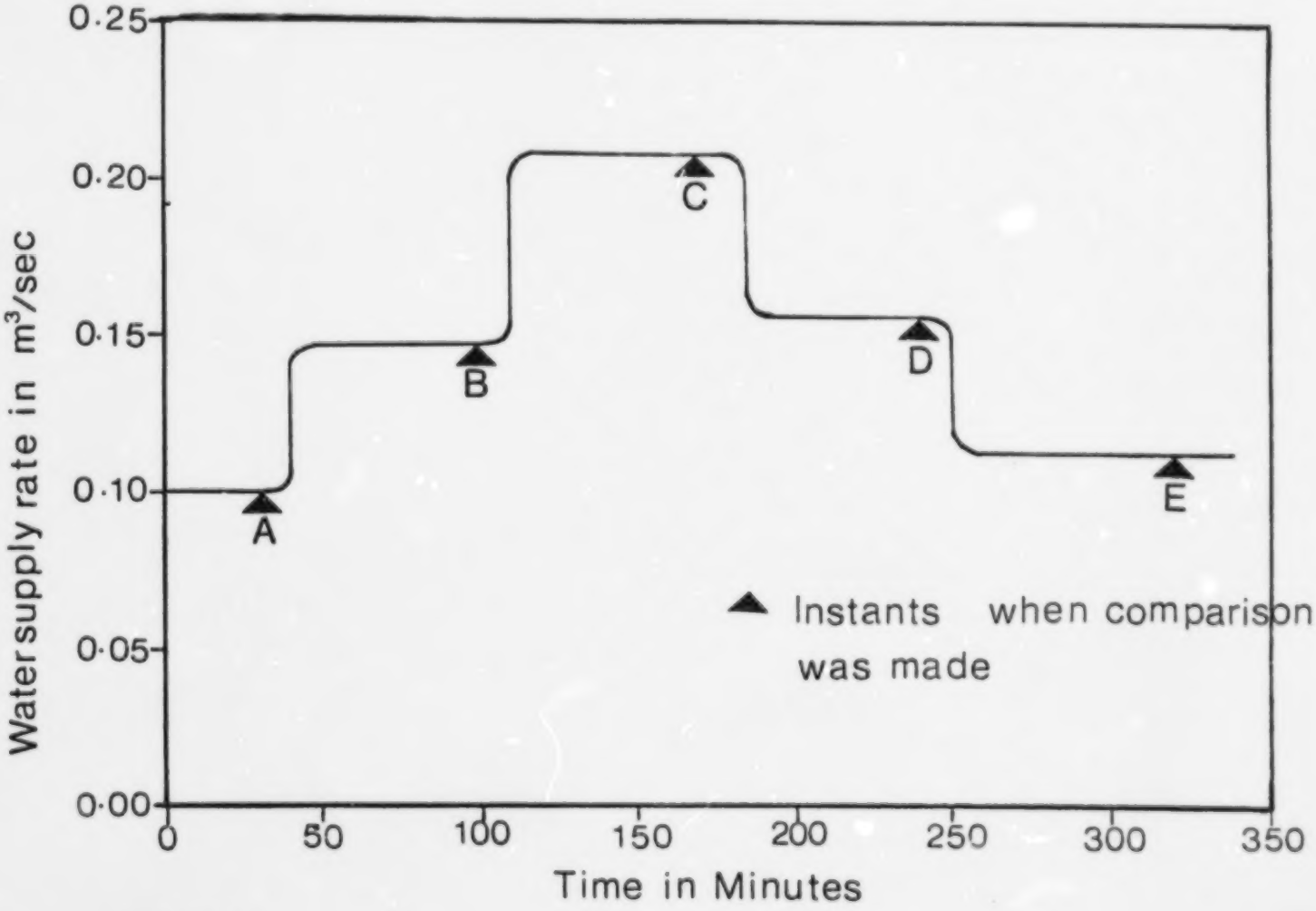
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FIGURE 4

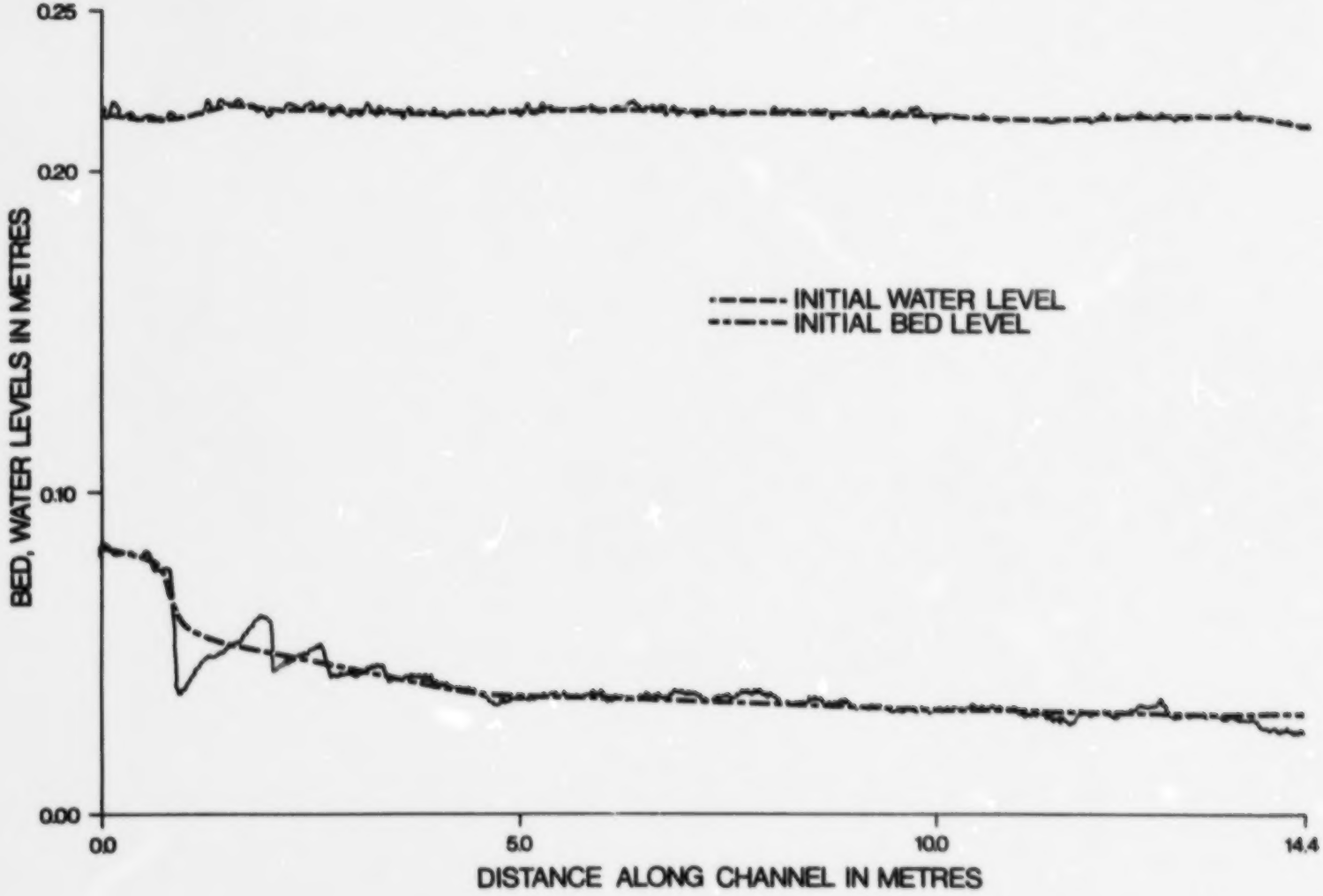


FIGURE 5 COMPARISON OF MODEL PREDICTIONS WITH LABORATORY MEASUREMENTS

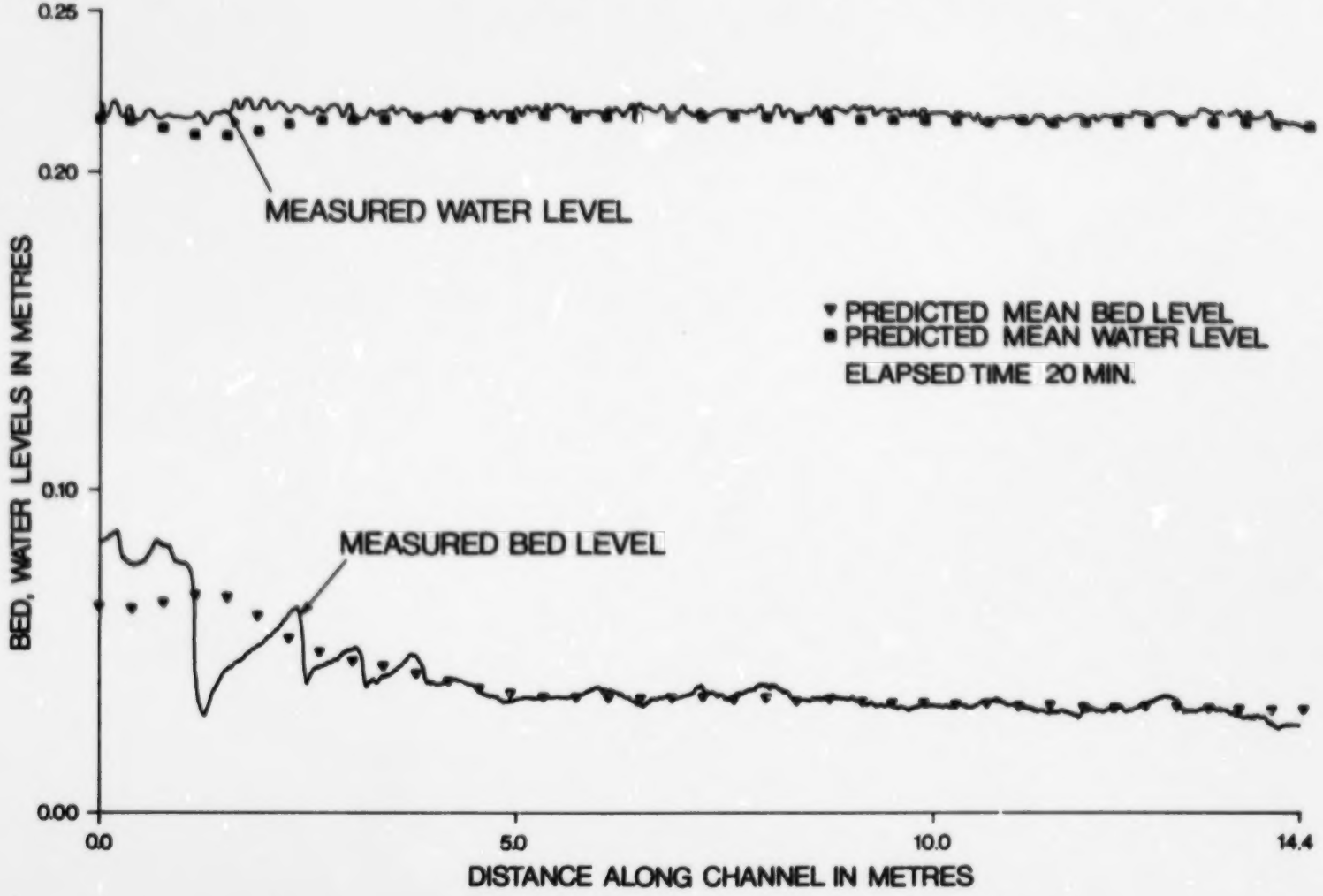
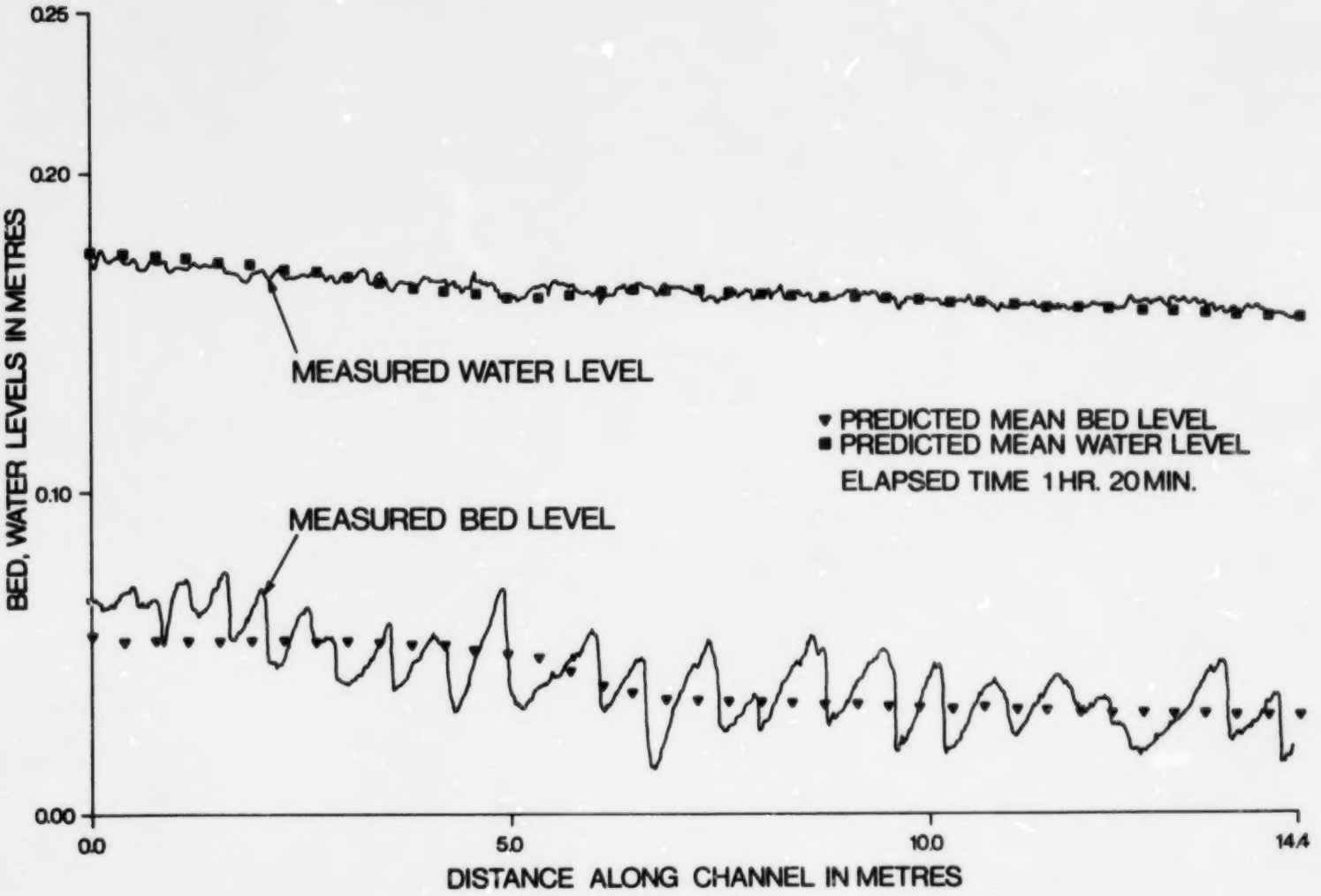


FIGURE 6 COMPARISON OF MODEL PREDICTIONS WITH LABORATORY MEASUREMENTS



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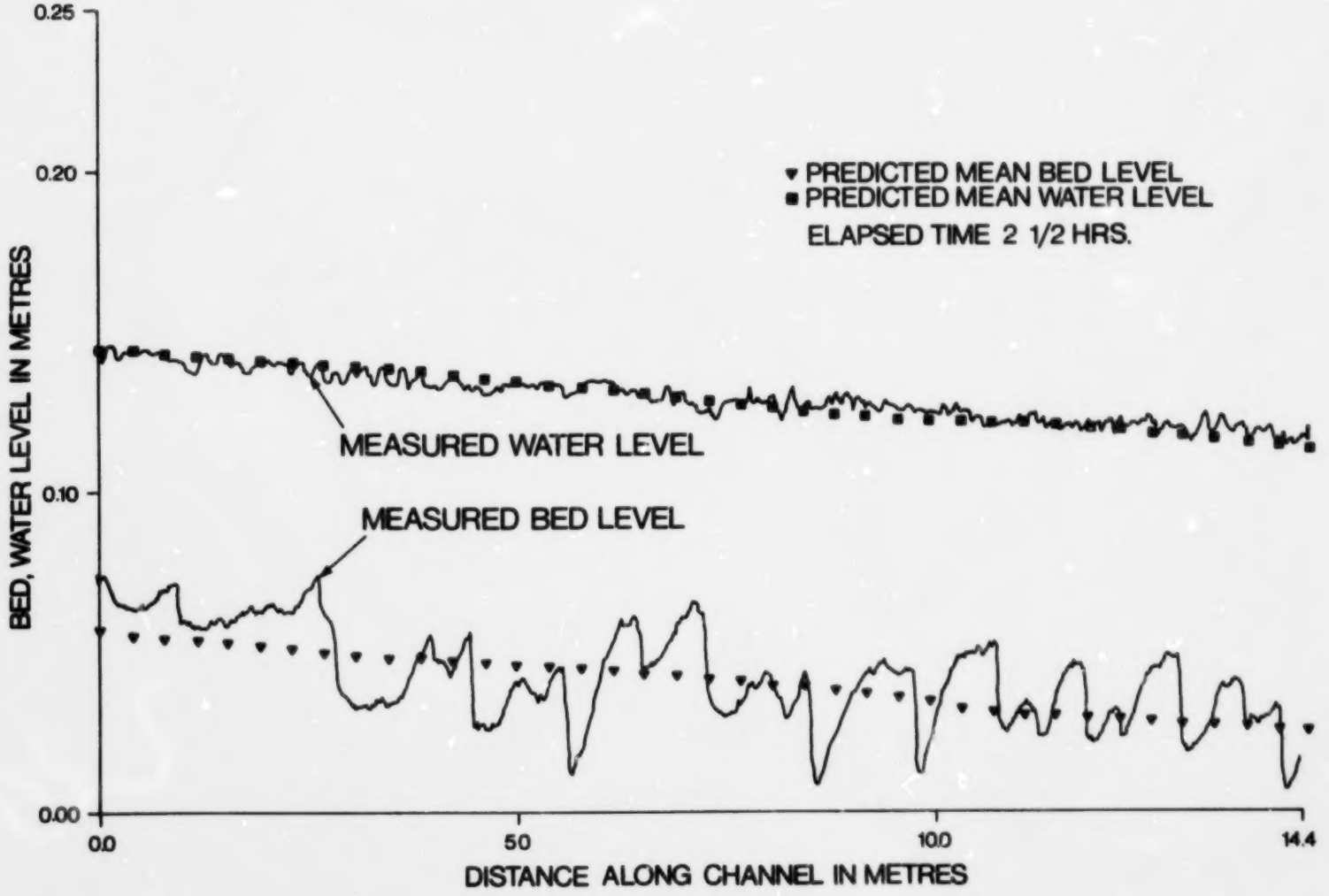

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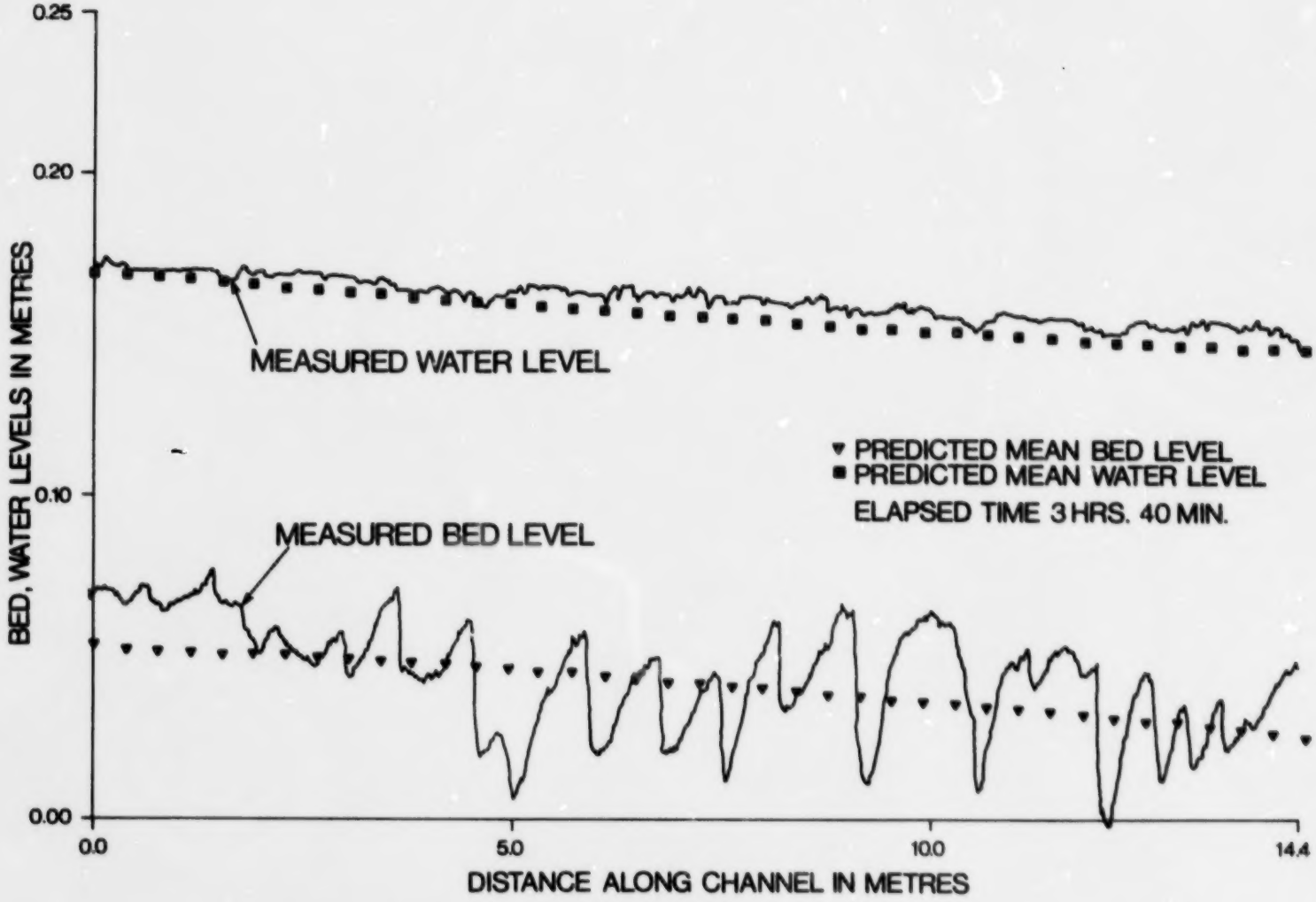

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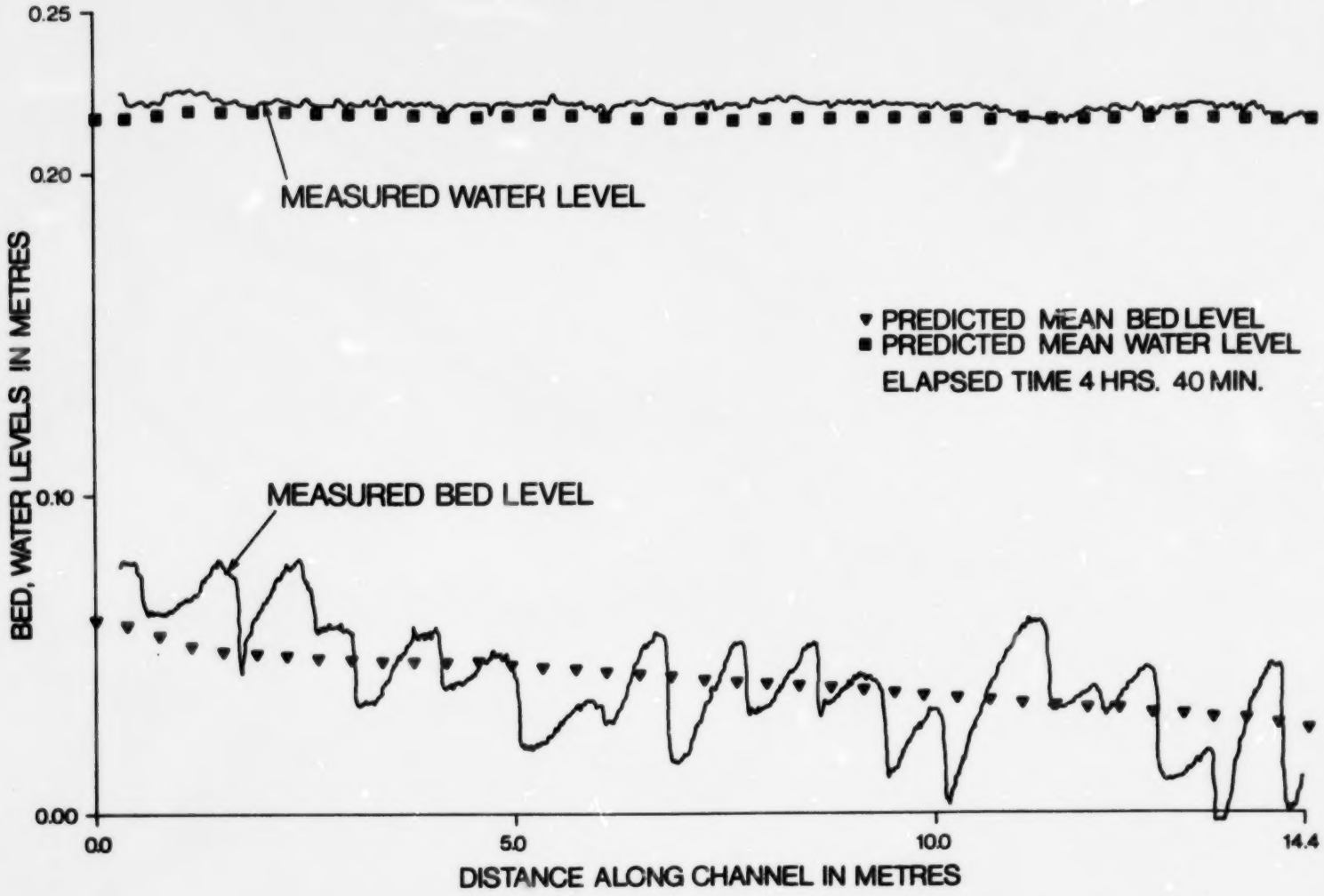

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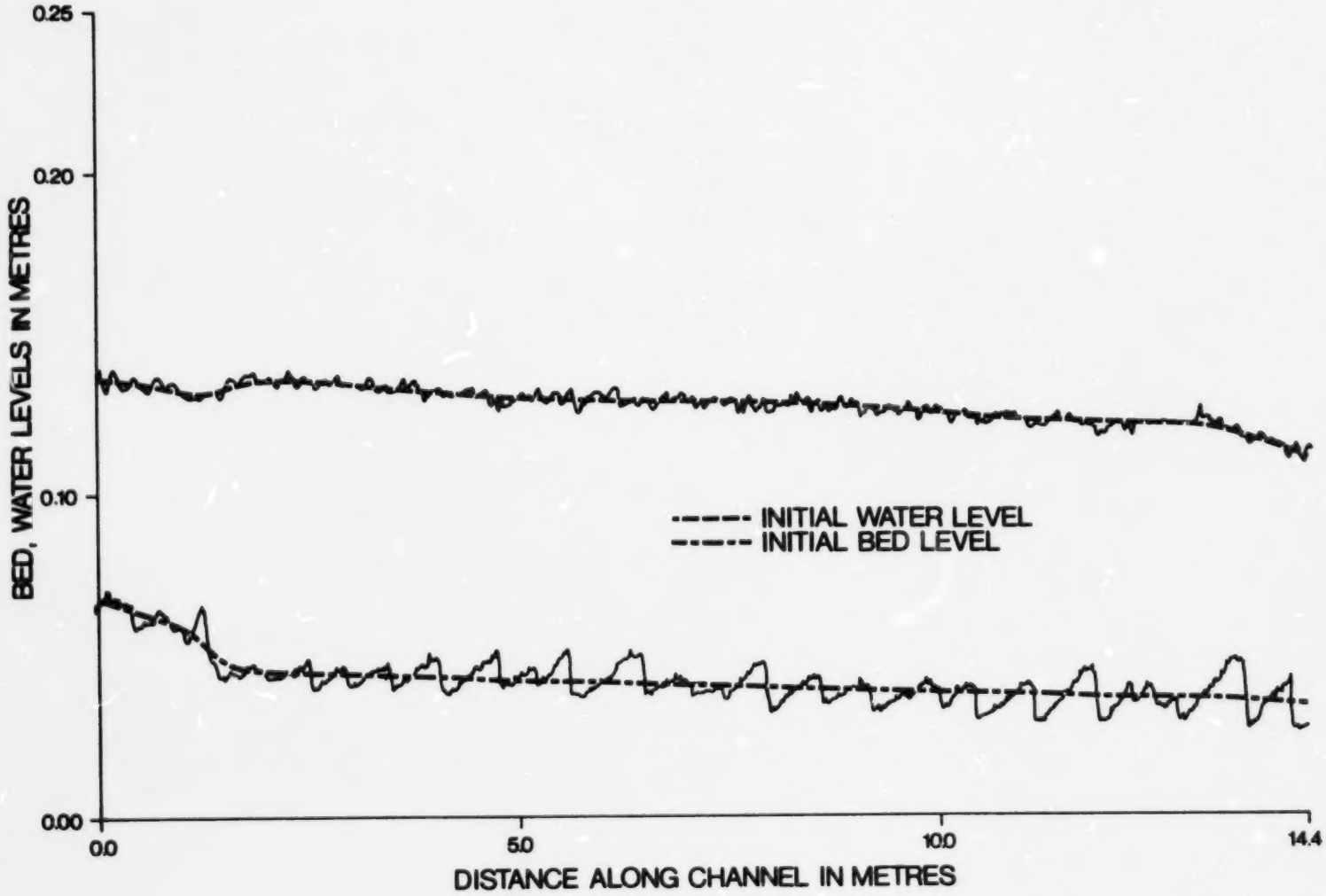

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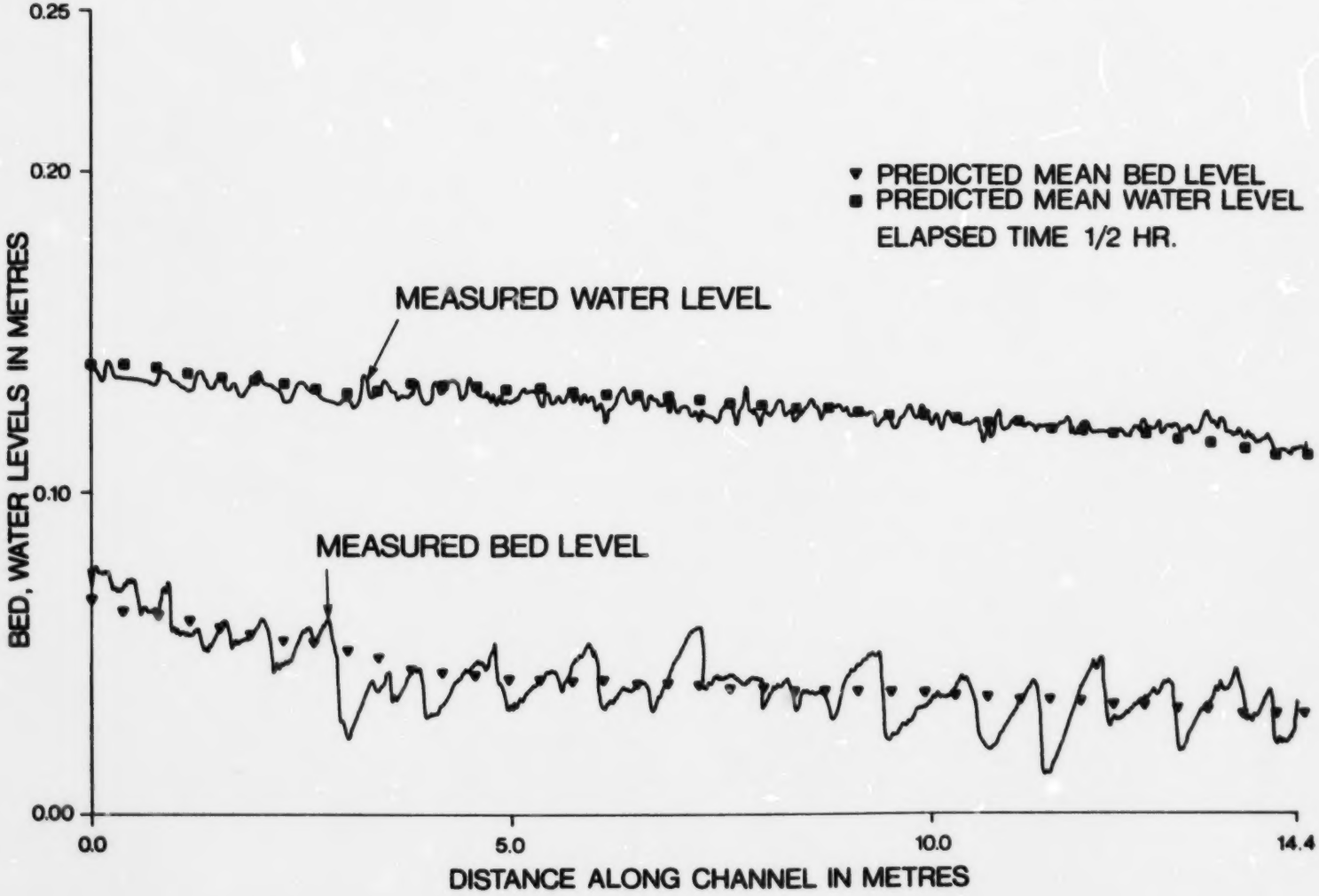

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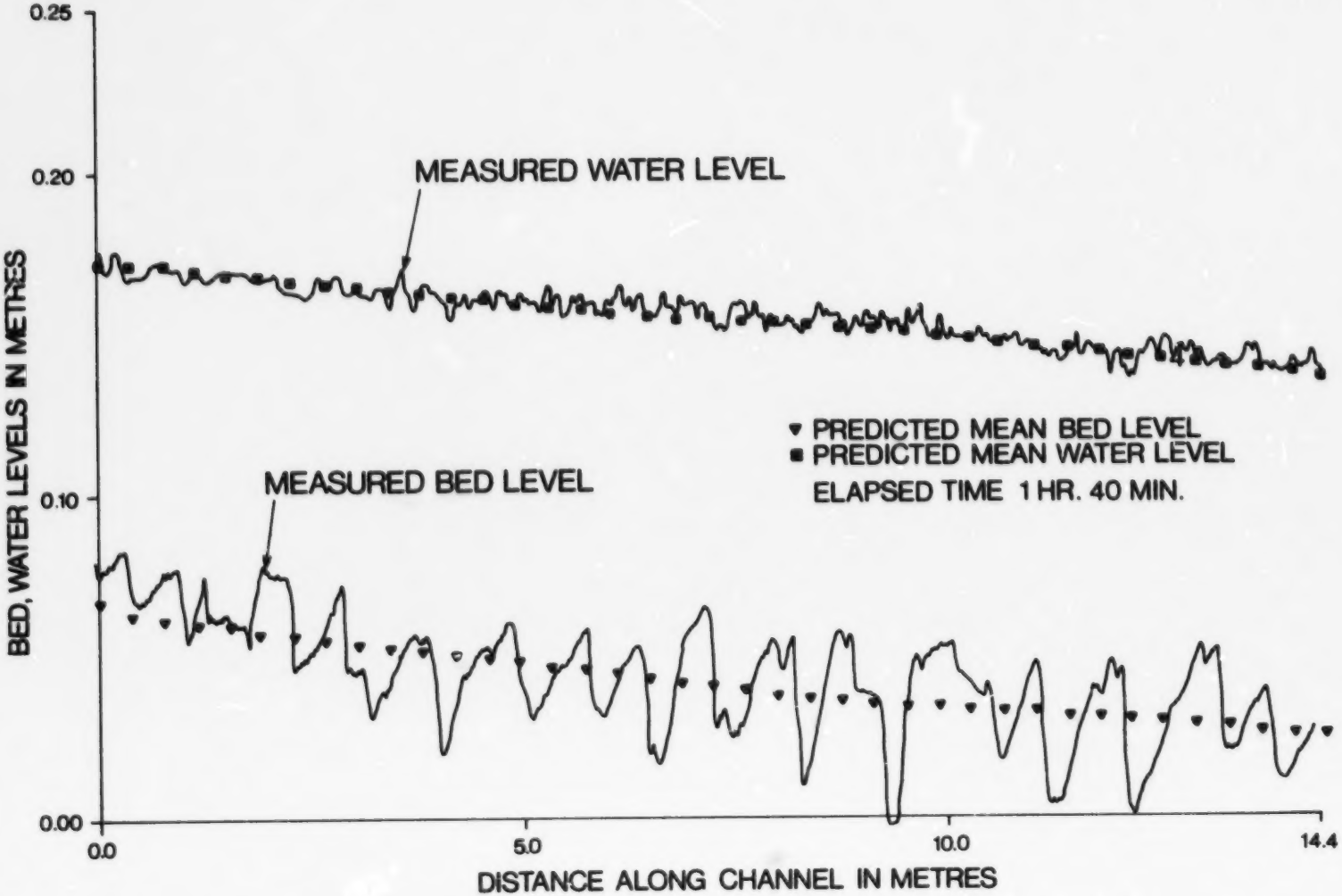


FIGURE 13 COMPARISON OF MODEL PREDICTIONS WITH LABORATORY MEASUREMENTS

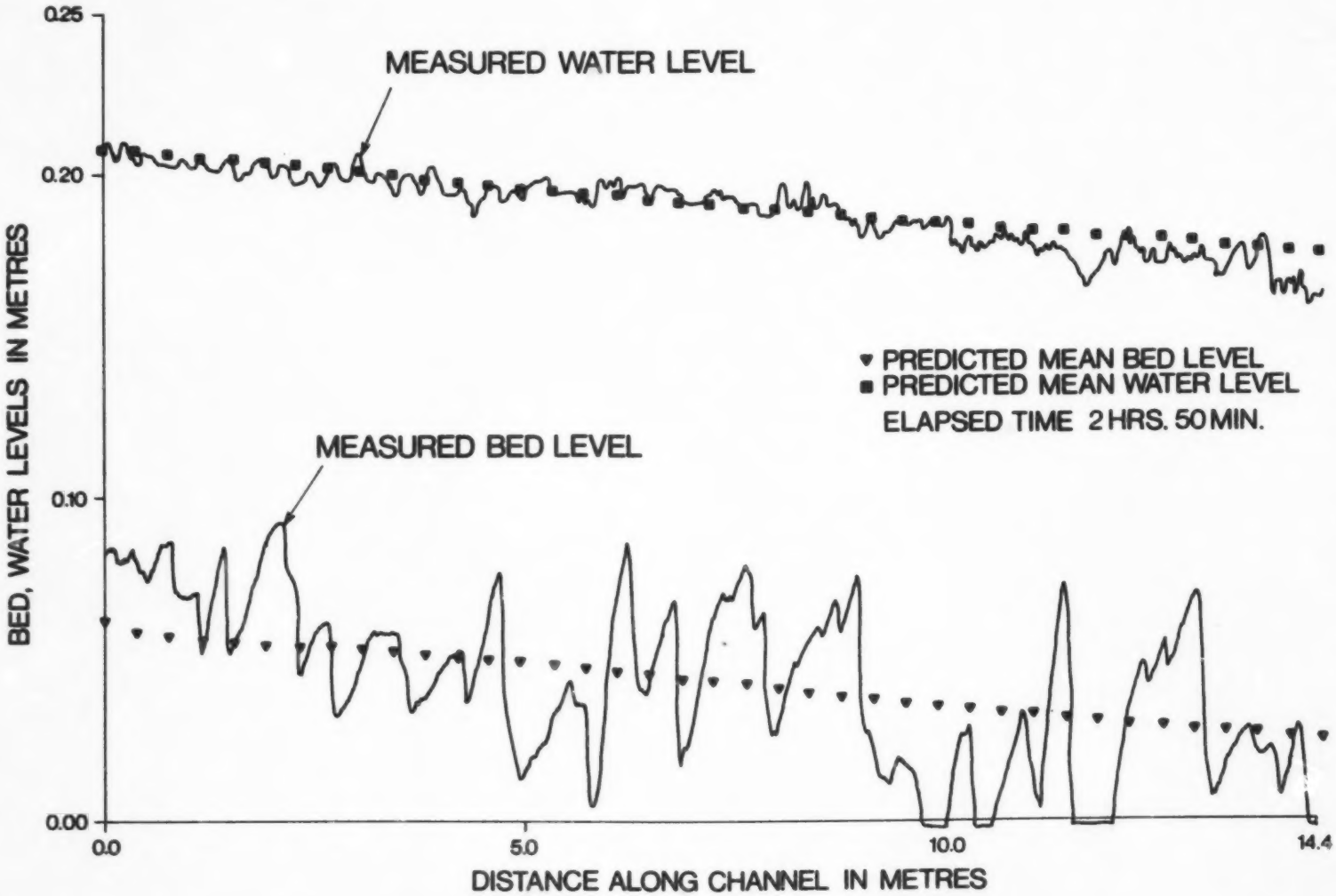
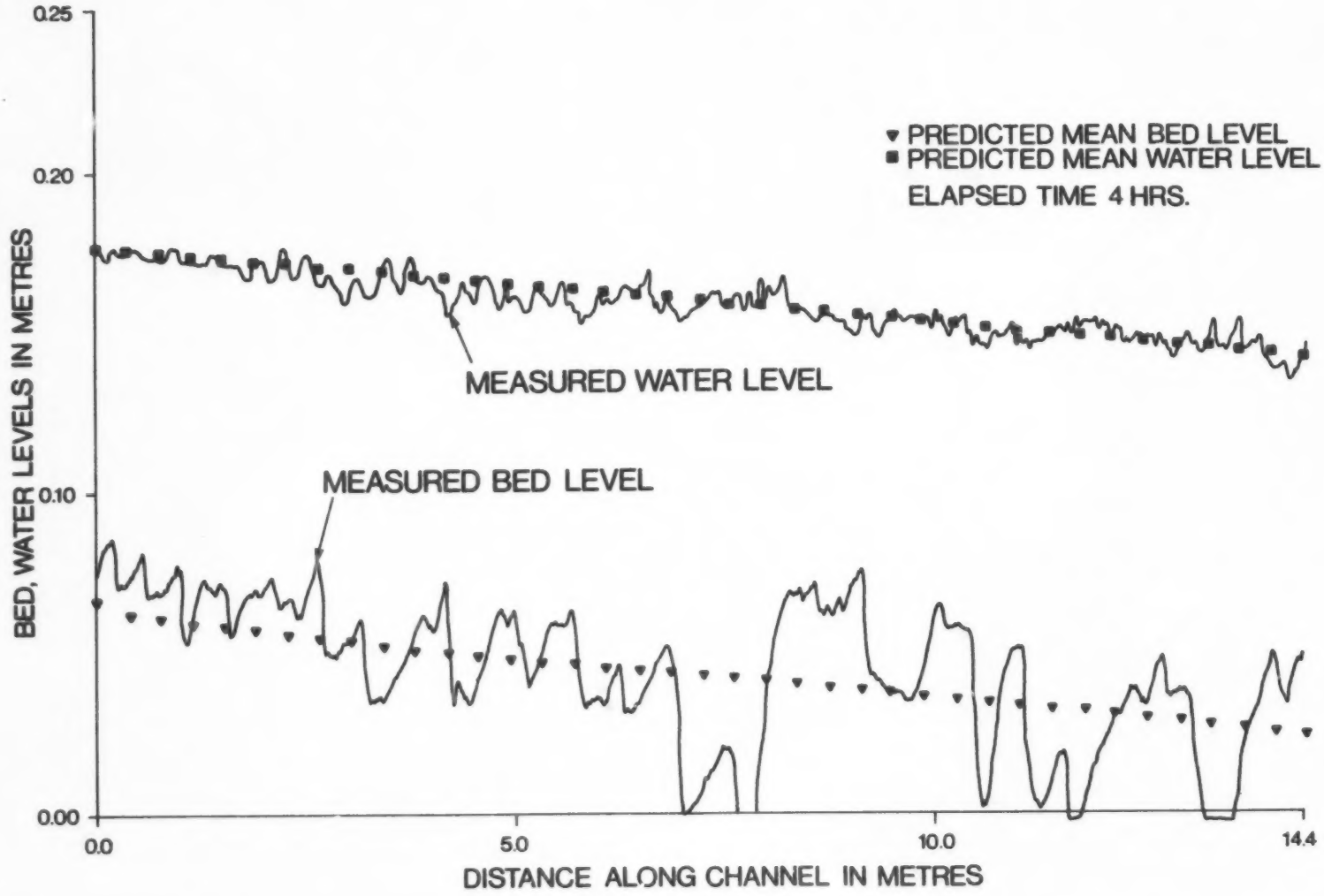


FIGURE 14 COMPARISON OF MODEL PREDICTIONS WITH LABORATORY MEASUREMENTS



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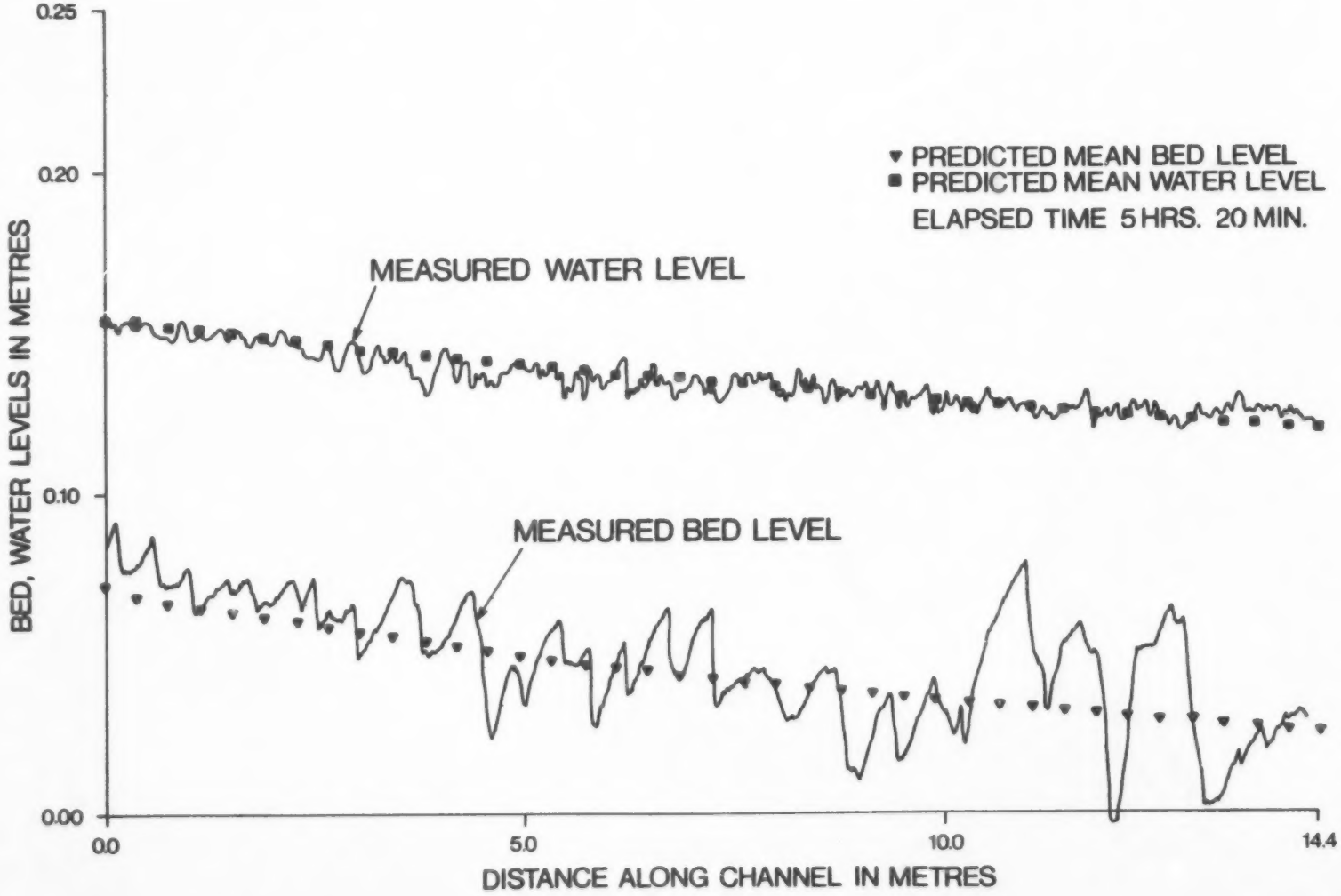

FIGURE 16 COMPARISON OF MODEL PREDICTIONS WITH LABORATORY MEASUREMENTS